Human impacts outpace natural processes in the Amazon

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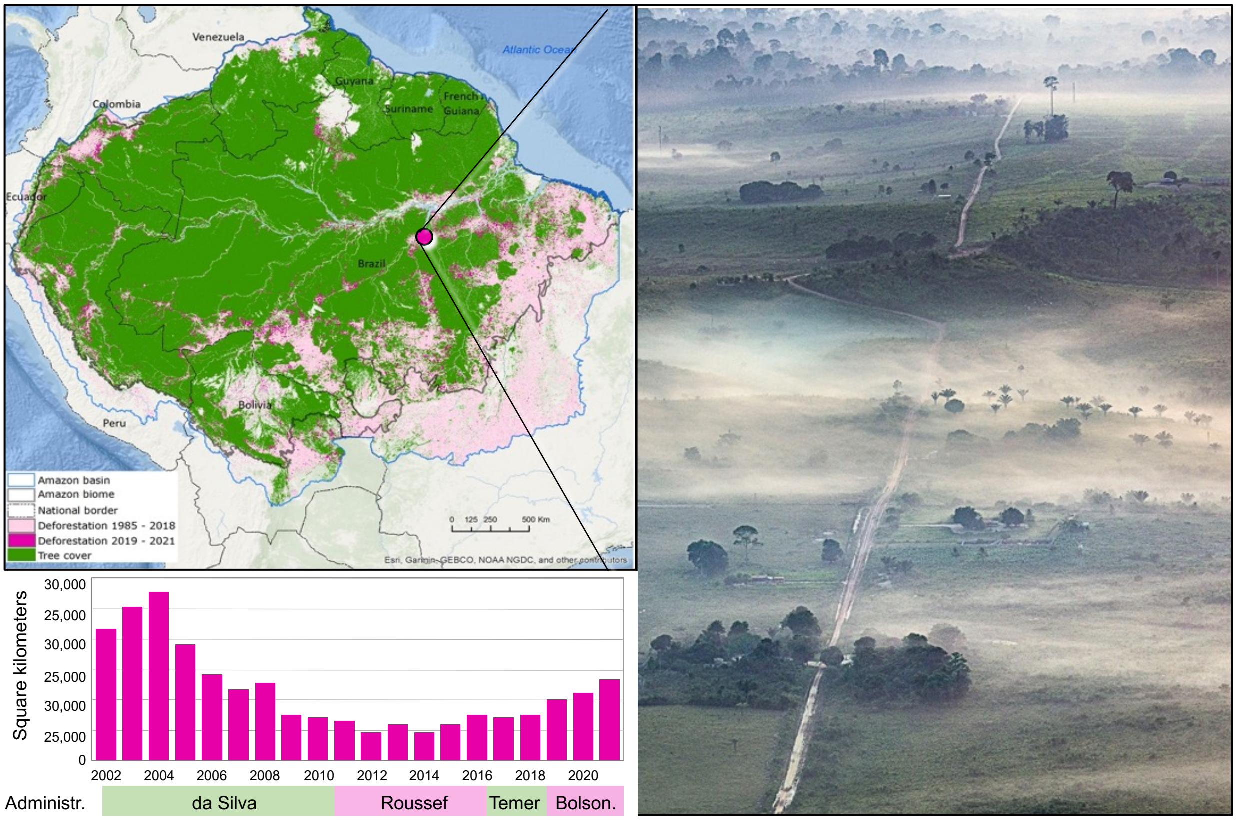

Summary figure: Amazon deforestation is accelerating from anthropogenic drivers, including drier climatic conditions and policies favoring industrialized agriculture. Top left: Map of Amazonia showing location of wildfires 2019-2021. Bottom left: Rate of deforestation in the Brazilian Amazon, now rising under environmental policies of the Bolsonaro administration. Data from *SPA Amazon Assessment Report 2021 Chapter 14*. Right: Recently burned primary forest near Rurópolis, State of Pará, Brazil, Sept. 17, 2020. Location indicated by colored circle at left (photo: M. Cruppe/Amazônia Real). Map produced in ArcGis10.8.2. Data from *Mapbioma Amazônia* (https://amazonia.mapbiomas.org/en) and *Amazonian Network for Socio-Environmental Information* (*RAISG*: https://www.raisg.org/en/). After millions of years serving as an immense global carbon pool the Amazon rainforest is becoming a net carbon source to the atmosphere.

Abstract (120 words)

Amazonian environments are being degraded by modern industrial and agricultural activities at a pace far above anything previously known, imperiling its vast biodiversity reserves and globally-important ecosystem services. The most substantial threats come from regional deforestation due to export market demands, and global climate change. The Amazon is currently perched to transition rapidly from a largely forested to a non-forested landscape. These changes are happening much too rapidly for Amazonian species, peoples, and ecosystems to respond adaptively. Policies to prevent the worst outcomes are known and must be enacted immediately. We now need political will and leadership to act on this information. To fail the Amazon is to fail the biosphere, and we to fail to act at our peril.

[Introduction]

The Amazon is a critical component of the Earth climate system whose fate is embedded within that of the larger planetary emergency. Along with the two polar ice sheets and coral reefs, the Amazon (*sensu 1*) is one of four major ecosystems of the Earth System that are rapidly approaching or surpassing the threshold to a qualitatively degraded state (*2*, *3*). The Amazon is by far the most species-rich subcontinental-scale ecosystem, being home to more than 10% of all named plant and vertebrate species concentrated into just 0.5% of Earth's surface area (*4*). Yet Amazonian biodiversity is grossly underestimated with perhaps only about 10% of the species yet described (*5*). Amazonian biodiversity is the evolutionary source for much of the world's plants and animals (*6*, *7*), serving as the core of a biogeographic realm that hosts about one-third of all known species on Earth (*8*).

The Amazon is also a crucial provider of global ecosystem services, contributing about 16% of all terrestrial photosynthetic productivity (*9*), and strongly regulating global carbon and water cycles (*10*, *11*). Yet global warming is rapidly increasing climate variability in the Amazon. Extreme droughts and record floods have occurred in nine of the last 15 years, compared to just four extreme droughts and three record floods in the previous century (*11*). These extreme weather events are substantially lowering the threshold for wildfires at the rainforest margins, altering biogeochemical cycles, and leading to widespread deforestation, habitat degradation and wetland loss (*9*, *12*).

Given the outsized role of the Amazon in our planetary hydrological cycle, large-scale deforestation threatens to push the whole Earth System across a critical threshold to a qualitatively different global climate regime (*13*). Quite aside from biodiversity losses, such a transformation will have multifarious and catastrophic consequences for human welfare, including widespread water and food insecurity (*14–16*) leading to mass migrations and political instability (*16*).

In this Review, we compare rates of anthropogenic and natural environmental changes in the Amazon and other regions of South America, and also compare these rates with other processes in the larger Earth System. Data for South America were compiled from the Science Panel for the Amazon (SPA) Assessment Report (*1*), which details the many dimensions of the Amazon as a regional entity of the Earth System. The SPA Report, co-authored by 240 scientists from 20 countries, including members of Indigenous Peoples and Local Communities (IPLCs), documents epoch-scale transformations in Amazonian biodiversity, ecosystem function, and cultural diversity. The Report also summarizes the major social and ecological transformations of the Amazon through human history, and presents sustainable development pathways for the Amazon into the near future. The key messages of this Review are that multiple strong changes to the Amazon being driven by modern human activities are happening far too fast for the survival of its species and ecosystems (*17*), and that widespread Amazon deforestation would be an irreversible catastrophe for the global climate system (*9*, *18*).

Amazon in motion

The Amazon is perched to transition rapidly from a largely natural to degraded and transformed landscapes, under the combined pressures of regional deforestation and global climate change (*19*, *20*). As of 2019, a cumulative total of about 17% of the pre-Columbian Amazon forest had been cleared, and 14% replaced, by human agriculture landscapes; 89% for pasture and 11% for crops (*21*). After millions of years serving as an immense global carbon pool, under further warming the Amazon rainforest is predicted to become a net carbon source to the atmosphere (e.g., *22*, *23*). Some parts of the Amazon have already made the transition, with forest respiration and burning outpacing forest photosynthesis (*24*).

As we enter the third decade of the 21st century, portions of the southern and eastern Amazon are changing to a disturbance-dominated regime (*25*, *26*). Under global drivers of climate change much of the Amazon is experiencing pronounced increases in the frequency and severity of floods, droughts and wildfires (*12*, *27*). The basin-wide impacts of landscape desiccation have far surpassed the variability of natural hydrological and biogeochemical cycles since the start of the current climate epoch, the Holocene, c. 11,700 years ago (*28*). Further, several other ecologically and biodiversity-rich regions of the Neotropics outside of the Amazon (e.g., Atlantic Rainforest or Mata Atlântica, Caatinga, Cerrado, Chocó, and Puna) are also facing accelerating threats from modern human activities (*1*, *7*).

Before the Anthropocene (starting *c*. 1945), the Amazon had maintained natural humid and tropical environments, including forests and wetlands, over most of lowland northern South America for tens of millions of years (*4*). Amazonian ecosystems have persisted through many profound climatic and evolutionary transformations, including the formation and draining of inland seas and mega-wetlands during most of the Miocene (c. 23–10 million years ago or Ma), and transitioned into a fluvial landscape in the late Miocene to Pliocene (c. 10–2.3 Ma; 29), alternating ice-age and interglacial climates during the Pleistocene (c. 2.6–0.01 Ma; *29*, *30*), and shifting land-use practices of Indigenous peoples during the Holocene (*31*).

Thus, quite unlike the expansive temperate and boreal forests of the northern hemisphere, which were repeatedly cleared and pushed southwards by low temperatures and continental glaciers during the Pleistocene (2.6–0.01 Ma) and then regenerated in the Holocene, Amazonian rainforests have never previously confronted regional-scale deforestation (*32*, *33*). This ecosystem persistence over evolutionary time scales resulted in the Amazon becoming both a center and source of biodiversity for the whole Neotropical region (*6*, *34*).

In the Amazon, more than in most other regions, forest-rainfall feedback is required to maintain the current forest cover (*35*). About half of the precipitation over the Amazon is recycled from evapotranspiration, with about 14.1 trillion cubic meters of water per year falling as precipitation over the whole basin, compared with the Amazon River discharge of about 7.3 trillion cubic meters per year. Amazonian forest cover buffers the ecosystem against variations in precipitation and fire (*36*, *37*). This dependence of the state of the system on its history (i.e., hysteresis) is a common feature of many ecological systems at large spatial and temporal scales, in which the observed state of a system cannot be predicted based on current conditions alone.

Amazon forest extent and structure is therefore highly sensitive to widespread forest degradation and removal (*38*, *39*). Clearcutting parts of the Amazon forest exposes the landscape to an irreversible regime shift, from a forested to a non-forested landscape, with a wide range of deleterious consequences (*12*, *40*). Beyond a certain threshold, deforestation and regional aridification will become locked in a vicious cycle that drives a runaway transformation of lush rainforests to degraded savannah-like agricultural landscapes (*25*, *41*).

Drivers of Amazon destruction and degradation

The main regional-scale drivers of Amazonian habitat destruction and degradation arise from land-use changes (e.g., deforestation, wildfires, soil erosion), water-use changes (e.g., damming and fragmenting rivers, increased sedimentation from deforestation, pollution from the mining of minerals and hydrocarbons, ground-water extraction), and aridification from global climate change (*5*, *18*). The main effects of climate change today are precipitation changes, and sea-level rise will likely have major effects in the near future. Over-hunting and overfishing (*42*), the introduction of invasive exotic species (*43*), and pollution (*44*) are additional important threats to biodiversity and ecosystem function at local to regional scales in the Amazon and other ecosystems. Here we focus on deforestation and carbon cycles because of their critical roles on the Amazon and Earth systems.

The most rapid environmental changes in the Amazon today are driven by land converted from forests and degraded pastures into soy and livestock production, primarily for export (*45*, *46*). By 2019 about 867,000 square kilometers or about 14% of the Amazon forest had been cleared, especially in the Brazilian states of Pará, Mato Grosso, Rondônia and Amazonas, in order of greatest contribution to deforestation (*21*). Between 1995 and 2017, 17% of the Amazon rainforest was degraded by logging, fire, windthrow or road expansion (*47*). Under the auspice of globalization, Amazonia is being integrated into global commodities markets, mostly soybean, beef, and timber (*48*).

The immediate crisis is driven by the logging and burning of closed-canopy tropical rainforests to clear land for agriculture and pasture. Agricultural expansion is the leading cause of regional deforestation worldwide and in South America (*49*, *50*). The legal construction of roads, dams, and other infrastructure, combined with many illegal activities (e.g., forest clearcutting, logging and burning, mining, illicit crops and clandestine roads) have driven the agricultural frontier deep into the Amazon margins over the past 20 years (*51*, *52*). During this same period, soybean exports from Brazil to China surged by 2,000%, primarily as animal feed to supply rapidly-increasing meat consumption in China, and South America is currently the largest source of biomass imports to the European Union (*53*).

The Great Soybean Plough-up of South America during the early 21st century is the farthest outlier of anthropogenic changes from the regression lines for South America in Fig. 1. This landscape transformation is roughly comparable in total area and proportion of landscape surface to other regional-scale "Great Plough-ups" of history, like the spread of grain culture across monsoon Asia from about 3,000 to 1,000 years ago, the Northern European plains from about 1,500 to 1,000 years ago, the Russian Steppes in the 18th and 19th Centuries, and the Great Plains of North America in the late 19th and early 20th century, and the ongoing expansion of palm oil plantations in Indonesia, Malaysia, and many other countries.

Effective forest-protection policies act by removing the international financing of market-driven land conversion projects. Two of the largest funding sources are Inter-American Development Bank (IDB) based in Washington DC (*54*), and the Belt and Road Initiative (BRI) of the Chinese government. The Initiative for the Integration of the Regional Infrastructure of South America (IIRSA) is a massive infrastructure program of road and dam construction launched in 2000. Most IIRSA environmental impacts derive from road construction in the Brazilian states of Amazonas and Acre, and the Colombian states of Caquetá and Guaviare, providing increased access for accelerated expansion of beef production, oil extraction, and mining (*55*).

BRI-financed hydroelectric and water diversion projects are planned to dredge and canalize hundreds of river kilometers in Ecuador and Perú (*56*). BRI-supported water diversion projects will expand soybean cultivation on more than 74,000 square kilometers, and hydrologically link Amazonian tributaries to neighboring drainages. Once completed these projects will convert major southern tributaries (e.g., Tapajos and Xingu rivers) into a network of artificial reservoirs with poorly-known but negative impacts to local biodiversity and IPLC livelihoods, and the function of regional hydrological systems (*57*).

The effectiveness of forest-protection policies has varied over the last 20 years (*52*, *58*). The Action Plan for the Prevention and Control of Deforestation in the Legal Amazon (PPCDAm), launched in 2004, improved the deforestation monitoring system, reinforced environmental inspections, and promoted land tenure for IPLCs in legally protected areas. These actions were strengthened over time, by the Soy Moratorium (from 2006) and the Black List of municipalities with highest deforestation rates (from 2008). Together these actions substantially reduced access of industrial farming interests to international markets and financial credit (*53*, *58*). However, more recent political actions by the Brazilian government have undermined the PPCDAm, markedly increasing deforestation rates since 2016. These actions have weakened environmental laws, especially the new Brazilian Forest Code, institutionally dismantled environmental agencies, and suppressed the Sugarcane Agroecological Zoning Act of 2009 (*59*).

Global climate change represents the other imminent threat to the Amazon and other ecosystems, impacting forest dynamics, carbon and nutrient cycling, freshwater, and coastal ecosystems (*60*, *61*). As predicted by climate models (*62*, *63*), and well documented by climatic records (*11*), precipitation patterns are becoming more variable in time and space, with more frequent and severe floods (*64*), and more persistent and widespread droughts (*39*). Climate change is rapidly desiccating the southern and eastern portions of the Amazon rainforest, contributing to higher frequency and severity of wildfires and contraction of the southern forest margin. Concomitant sea-level rise is projected to inundate the biodiverse floodplain and coastal mangroves and estuaries, converting them to nearshore marine habitats and threatening coastal livelihoods (*65*).

How fast is the Amazon changing?

We compiled age and area estimates for 55 different anthropogenic and natural processes affecting terrestrial and aquatic ecosystems in South America and globally, including 11 anthropogenic and 21 natural processes in the former, and 13 and 11 processes in the latter (Table 1). Ensemble rates were assessed by the exponent value of power-function regressions applied to each of these four categories.

We find that rates of anthropogenic processes affecting Amazonian ecosystems are up to hundreds to thousands of times faster than they are for natural climatic and geological phenomena (Fig. 1).

These anthropogenic changes have reached the scale of millions of square kilometers within just decades to centuries, as compared with millions to tens of millions of years for evolutionary, climatic and geological processes. Destruction of Amazonian environments is far outpacing species, ecological interactions, and ecosystems capacity to respond adaptively (*32*, *66*). The rate at which modern human activities is driving extinctions in the Neotropics is between 1,000 and 10,000 times higher than the natural or 'background' rate as estimated from the fossil record (*17*, *67*).

These anthropogenic changes to Amazonian environments are coupled to processes worldwide, racing ahead many times faster than those of natural counterbalancing processes in the Earth System (*68*). Among the most important ongoing imbalances are accelerating rates of climate change (*69*), sea-level rise (*70*), terrestrial vegetation turnover (*32*), river delta avulsion (*71*), tropical deforestation (*72*, *73*), extinction (*74*), and soil erosion and waterway sedimentation (*75*–*77*). While the residence time of carbon through the atmosphere, hydrosphere, and lithosphere is on the order of millennia to millions of years, modern human extraction and burning of fossil fuels occurs at time frames of decades to centuries (*78*). Global climate changes during the last deglaciation (e.g. Pleistocene-Holocene transition) occurred on the time frame of centuries to millennia as compared with ongoing anthropogenic changes that are observed at a decadal scale (*79*).

Given the key role of the Amazon in the Earth system, the causes and consequences of Amazonian and global system degradation are strongly linked (*1*), and the pace of anthropogenic changes exceeds that of many natural processes at regional to global scales (Fig. 1). For example, average annual global deforestation over the past decade has exceeded afforestation by about 100,000 square kilometers, causing a net loss of forest of about 1.4% every year (*80*). Global soil erosion exceeded soil formation by 35.9 billion tons (Gt) in 2012, representing a 2.5% increase over the erosion estimate from 2001 (*81*). Rates of vegetation change equal or exceed the deglacial rates globally, indicating the scale of human effects on terrestrial ecosystems now exceeds the massive vegetation transformations during the last major global climate change event (*32*). In the Amazon, changes in the precipitation patterns, because of deforestation or withdrawal, are having a strong impact on the frequency and magnitude of intermittency of rivers and streams specially in the southeastern part of the Amazon. Lastly, while accurate data on groundwater withdrawals are difficult to collect, estimates indicate that depletion far exceeds recharging in most parts of the world, with net losses of up to 20% per year in some highly populated and aridifying regions of North America and Asia (*82*).

Global consequences of Amazon degradation

From a climate perspective, widespread Amazon degradation would be an irreversible global catastrophe. Amazonian forests and soils contain about 180 ± 30 billion tons (gigatons) of carbon (GtC); approximately half of this carbon is stocked in the form of vegetation biomass and the other half remains as soil carbon stocks (*9*). By comparison, this Amazonian carbon volume is equivalent to about 26% of the 690 ± 80 GtC released into the atmosphere by all human activities since the Industrial Revolution (1750–2020), achieved primarily by burning fossil fuels and land-use changes (*83*). Anthropogenic carbon emissions during this time period raised atmospheric CO_2 from 277 to 415 ppm, and increased the average global temperature to 1.2 °C above preindustrial levels. Releasing all the Amazonian carbon into the atmosphere would initially increase the airborne CO_2 concentration by an additional 85 ppm, representing another concerning c. 0.5 °C increase (*83*).

Under the 2015 Paris Climate Accords, to keep atmosphere warming below 2°C global civilization cannot emit more than 465 Gt more carbon, and the Amazon alone contains about 32–44% of that carbon total. Yet Amazonian fires from 2010 to 2018 released about 0.5-1.5 GtC per year into the atmosphere, while forest growth during this time period removed only about 0.5 GtC per year (*84*). The approximately 4.5-9.0 GtC left in the atmosphere is similar to total carbon emissions of Japan during this interval, which ranked fifth among nations for carbon pollution (*85*). In order to better judge the volume of Amazon carbon impact on global climate, it should be noted that Amazonian afforestation in the centuries after the Iberian conquest (c. 1500 - 1700) captured about 7.4 GtC (3.5 ppm CO_2 equivalent) from the atmosphere, perhaps contributing to the global cooling episode known as the Little Ice Age (*86*).

The adverse consequences of global anthropogenic carbon emissions extend beyond the Amazon to the whole Earth System. Without sufficient abatement, melting polar ice sheets will contribute more than 13 m (c. 43 ft) to global sea-level rise by 2500, with complete loss of the Earth's ice sheets projected within the next 400 to 700 years (*87*). Ongoing melting of the Western Antarctic is projected to fragment the Thwaites Eastern Ice Shelf within the next five years, raising sea levels by more than 0.6 m and destabilizing neighboring glaciers (*88*, *89*). In an ice-free world, global sea levels would reach c. 65 m (c. 213 ft) above the present level, as high as they were in the super-greenhouse world of the Eocene about 56 million years ago (*90*). Such melting would raise the global sea level 93–162 mm per year averaged over the next few centuries, starting slow (averaging 3.1 mm year in the past 30 years), and accelerating towards the final collapse of the ice sheets. By comparison, sea levels rose about 60 m during the early and mid-Holocene (11,700–7,000 years ago), at an average rate of about 12.9 mm per year (*91*). Thus, the potential anthropogenic rate of sea-level rise in the next few years and decades is more than seven times faster than the maximum recorded rate after the last global deglaciation.

The rapid pace of human activities is readily seen in Stommel diagrams plotting the characteristic temporal and spatial scales of disparate human economic, geological, climatological and biological processes (Fig. 2). In this context it is useful to compare the modern anthropogenic biodiversity and climate crises with the Paleocene-Eocene Thermal Maximum (PETM) event, a global but relatively brief hyperthermal episode that occurred about 55.5–54.5 million years ago. During the PETM atmospheric CO_2 rose to the highest levels of the Cenozoic Era and the global average temperature spiked about 5–8°C to a temperature about 9–14 °C warmer than today, driving large changes to the geographic ranges and adaptive traits of many terrestrial and marine organisms (*92*). By contrast, current rates of change in CO_2 and global average temperature are hundreds of times faster than were during the PETM (*93*, *94*). Such unprecedentedly high rates of environmental change constitute the most important challenges to adaptation and persistence of plant and animal species in Amazonian ecosystems, and to global civilization (*95*).

Transformative pathways for sustainable development

The current state and future fate of the Amazon are inextricably bound to that of the entire Neotropical region, the global biosphere as a whole, and the future of civilization worldwide (*45*, *48*, *96*). Preserving Amazonian biodiversity and ecosystem services will require fundamental changes to legal, economic, and energy systems at both regional and global scales. Policy actions must be implemented to reverse climate change and reduce economic incentives in the international trade system that support export-driven economic development (*97*). These changes to international legal and economic systems must deliberately be built into the next phase of the

Anthropocene, when civilization transitions from carbon-based to renewable energy technologies, and a bioeconomy of standing forest and flowing rivers with sustainable governance (*98*, *99*).

A new legal framework. Successful economic development in many parts of the world has historically rested on a robust legal framework that incentives prosocial -- and disincentivizes antisocial -- behaviors and activities (*100–102*). Recent advances in environmental ethics and international justice provide robust legal standing for natural entities like landscape features (rivers, forests) and non-human species (*103*, *104*). For example, in a landmark ruling the Constitutional Court of Ecuador applied the constitutional provision on the "Rights of Nature" to safeguard cloud forests from mining concessions (*4*, *105*). This legal precedent was grounded in decades of scholarship (*106*, *107*) and similar laws have been codified in other countries (see (*98*, *108*)). "Earth system law" provides a complementary approach for addressing gaps in governance that arise from improper deregulation and dispersed regulatory architecture across institutions and geographic regions (*25*, *109*). These legal tools can be designed to criminalize activities that wantonly and substantially damage or destroy Amazonian ecosystems, or that harm the health and well-being of Amazonian species, by imposing criminal penalties of heavy fines and imprisonment (*110*, *111*). The importance of legal mechanisms in landscape preservation is well-illustrated the success of the PPCDAm in reducing deforestation in Brazil from 2004 to 2015, and by decisions made at the federal level to not prosecute illegal activities which dramatically accelerated deforestation from 2016 to 2022 (*112*).

A new Amazonian bioeconomy. The sustainable use of biodiversity resources is an important path for developing Amazonian economies to become integrated into the international economy under advantageous conditions (*99*). More than 40 million people inhabit the Amazon region, with more than 65% living in urban areas, all of whom are affected by climate change. IPLCs play a critical role in shaping, protecting and restoring ecosystems, biodiversity and cultural diversity in the Amazon (*113*, *114*). A successful bioeconomy extends beyond extractive and export-based economic activities (e.g., lumber, mining, soy, cattle), by prioritizing and monetizing biodiversity and ecosystem services, and promoting broad development goals in education, health, sanitation, and employment. Improving the quality of life of the Amazonian population, both in urban, peri-urban, and rural areas, is one of the principles of a bioeconomy based on standing forests and flowing rivers.

Desired outcomes of a new Amazonian bioeconomy optimize carbon sequestration, biodiversity recovery and human livelihoods (*115*, *116*). Sustainable bioeconomic development projects are most effective when they integrate modern scientific and commercial resources of urban communities with the traditional knowledge and skills accumulated by Indigenous and local farming communities over many generations (*48*). Lasting sustainability means prolonged co-existence of natural and human economic and social systems, and Amazonian development projects must therefore meet the immediate and long-term needs of the Amazonian population. Paramount among these needs are high-quality communication and transportation services to improve the commercialization of products, as well as institutional investments and international collaborations that support education, science and technology institutions located within the Amazon. The installation of any new large-scale infrastructure projects (e.g., mega-dams, transportation arteries exceeding 500 km) must be avoided and replaced by low impact alternatives (*118*). Mining initiatives that threaten Indigenous lands, the health of all Amazonian inhabitants, and biodiversity should also be avoided.

Resilient planning and management of Amazonian bioresources must necessarily prioritize the social and political actions that preserve species, habitat diversity, and functional redundancy, manage connectivity and feedback that stabilize longer-term processes over decades, promote reciprocal cultural and educational exchanges, and enhance integrated and decentralized (vs. hierarchical and centralized) governance (*117–119*). Rates of deforestation in the Amazon since 2000 have closely responded to policy changes enacted at the national level that affect these kinds of social and political actions (*118*, *119*).

In stark contrast, market mechanisms based on international commodity pricing have entirely failed to assess the real economic and social values of Amazonian landscape and ecosystem resources (*99*, *120*). Further, prospects are dim for using market forces in landscape conservation efforts in the near future (*51*). Public policies to correct these market failures are available, modelled from strategies successfully employed in other regions of the world where standing forests and flowing rivers have been allowed to persist for multiple decades, even under the context of intensive economic development (*121*, *122*). These policies successfully price the full market value of ecosystem services, provide incentives for activities that support forest and river preservation, and impose penalties for predatory and negligent actions (*123*).

The Grand Energy Transition. Preserving Amazonian biodiversity and ecosystem services requires modifying economic incentives in the international trade system that drive export-driven development (*97*). Such a "Grand Energy Transition" is already well underway (*124*), as the average cost per unit energy for renewable energies has fallen below that of fossil fuels in aggregate for the first time in human history (*125*). Yet the barriers to complete this transition remain high, including the high costs of infrastructure installation, and resistance by powerful stakeholders of the carbon economy (*126*) One of the biggest challenges is the high volume of fossil carbon still sequestered within the lithosphere; about 60% of oil and fossil methane gas and 90% of coal must be left in the ground to limit global warming to 1.5 °C (*127*).

Yet time is running short. Emerging technologies, social innovations, and broader shifts in cultural practices are being implemented to support a resilient biosphere and help maintain a healthy Amazon (*95*, *128*). These shifts can be accelerated with economic and legal actions that support a post-carbon global economy that includes alternative energies, CO_2 capture and sequestration, and possibly geoengineering. New socioeconomic innovations must prioritize circular economic supply and waste networks, and nurture green values and land ethics. New political and ecological innovations require coordination among leaders from the local, regional and national levels. Widespread public support for greener development has already had qualitative impacts in many settings and public awareness must be increased in Amazonian countries to influence elections and political decisions concerning environmental protection (*129*).

Policy actions and priorities. Long-term (decades to centuries) conservation critically relies on economic and legal support to Amazonian universities, research institutions and scientific collections. These academic institutions are uniquely situated to document Amazonian systems at multiple structural, geographic and temporal scales, and to characterize poorly-known organisms (e.g. plants, fungi, invertebrates and microbes), which are the "ecosystem engineers" regulating biogeochemical cycles in Amazonian soils, surface and ground waters. These institutions also provide the skilled labor force required to monitor Amazonian environments through time, and to train the next generation of Amazonian scientists.

Yet action is also required at broader scales. The global community must work closely and swiftly with national governments whose sovereignty includes Amazonian territory to enact economic, legal and scientific actions that limit global warming to 1.5°C above pre-industrial levels (*130*), and disincentive activities for commodity export, especially soy, beef, timber, mineral and hydrocarbon extraction (*133*). These actions are abstracted from the SPA Assessment Report (*1, 134*) and other recent global environmental assessments (*131*, *132*). These actions recognize the knowledge and rights of IPLCs, who play a critical role in shaping, protecting and restoring ecosystems and biodiversity in the Amazon and other tropical regions (*25*, *133*, *134*).

The most effective conservation actions enhance legal protections and punish illegal activities for areas under public, private, community, and Indigenous management, and reward companies, agencies and communities committed to sustainable economic practices(*134–137*). These actions prioritize partnerships with IPLCs, areas with unique and threatened species, ecosystems, culturally important landforms, and areas with the highest anthropogenic threat; i.e. with the most rapidly expanding human footprint. International financial institutions (e.g. IDB, BRI) must immediately suspend funding for IIRSA mega-infrastructure projects (e.g. roads, bridges, railways, dams, ports, mines, etc.) in Amazonia, pending thorough, independent, and regional-scale environmental assessments (*135*). Annual commodity supply chain reports of imports by country will enhance accountability. Success critically relies on robust, long-term partnerships among Amazonian people in the business, scientific, and IPLC communities. These partnerships provide sustained administrative, financial, and legal resources to IPLCs to secure land tenure rights, monitor, protect, and restore Amazonian ecosystems and biodiversity, and exchange biodiversity and conservation information between academic and local knowledge bases.

As we approach an irreversible tipping point for Amazonia, the global community must act now. Policies to prevent the worst outcomes have been successfully identified; their implementation is only a matter of leadership and political will. To fail the Amazon is to fail the biosphere, and we fail to act at our own peril.

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Figures

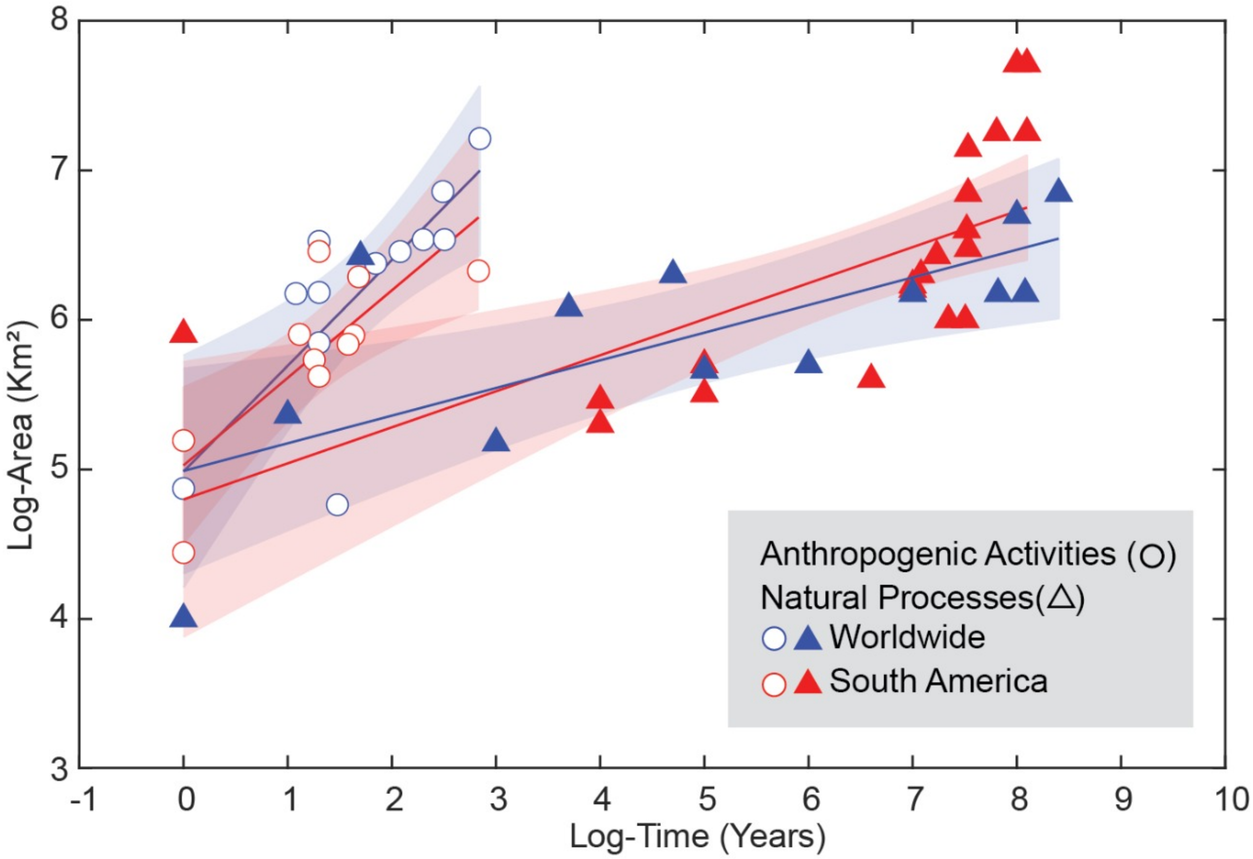

Fig. 1. Temporal and spatial scales of anthropogenic and natural processes in the Earth system. Data for 55 cases with references in Table 1. Circles and triangles represent anthropogenic and natural processes, respectively; red and blue symbols represent processes from South America and globally, respectively. All regressions are power functions represented as linear curves on a log-log plot. Anthropogenic South America (n=10), $y = 106443x^{0.5853}$, $R^2 = 0.2455$. Anthropogenic global (n=12), $y = 96870x^{0.7071}$, $R^2 = 0.8214$. Natural South America (n=21), $y = 102364x^{0.185}$, $R^2 = 0.4565$. Natural global (n=13), $y = 97678x^{0.1849}$, $R^2 = 0.4669$. Note anthropogenic processes occur at rates several orders of magnitude faster than natural processes.

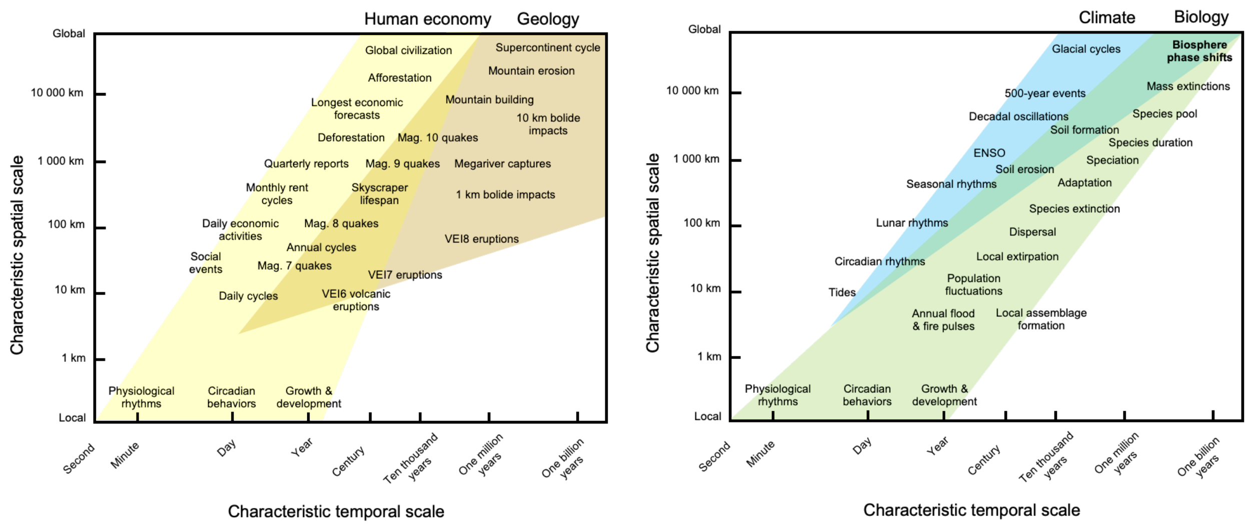

Fig 2. Stommel diagrams estimating the temporal and spatial scales for 52 natural processes across four domains. Human economy (*73*, *76*, *77*, *138–142*), geology (*143–152*), climate (*81*, *153*, *154*) and biology (*155–157*). Axes plotted using logarithmic scales, with log seconds on the horizontal axis and log km on the vertical axis. Biosphere phase shifts (at top right) include long-wave climate (i.e., greenhouse-icehouse) cycles, and unique events like Neoproterozoic formation of an oxidizing atmosphere, Cambrian explosion of animal body plans, Devonian colonization of the continents and formation of terrestrial biotas, and the Anthropocene climate and biodiversity crises. Note human economic activities affect larger spatial scales more rapidly than do most other natural processes.

Table 1. Anthropogenic and natural processes affecting terrestrial and aquatic ecosystems. Data unique to the Amazon indicated with an asterix.

Category	Process	Age	Area km^2	References	Notes
Anthropogenic Global	Land equipped for irrigation: 1700-2020	320	3,442,500	(*136*, *137*, *158*)	
	Wetland loss: 1700-2009	309	7,220,000	(*159*)	
	Freshwater withdrawals: 1800-2000	200	3,443,500	(*160*, *161*)	
	Land equipped for irrigation since 1900	120	2,863,500	(*136*, *137*, *158*)	
	Land equipped for irrigation since 1950	70	2,383,500	(*136*, *137*, *158*)	
	Urban land expansion: 1970-2000	30	58,000	(*162*)	
	Land equipped for irrigation since 2000	20	703,500	(*136*, *137*, *158*)	
	Urban land expansion: 2010-2030	20	1,527,000	(*162*)	Most likely forecast
	Habitat loss from agricultural expansion: 2020-2050	20	3,350,000	(*69*)	
	Global forest cover loss: 2000-2012	12	1,500,000	(*163*)	Forests with >50% tree cover
	Global deforestation: 2012	1	74,532	(*163*)	Forests with >50% tree cover
Anthropogenic South America	Marine incursions to 80 M: by 2700	680	2,125,900	(*164*)	Area estimated from maps using ImageJ
	Rangeland decertified S. America: 1960-2008	48	1,943,000	(*165*)	Area estimated from claim of 30% loss
	Amazon deforestation* 1975-2018	43	788,353	(*20*)	
	Petroleum concessions *: 1970-2008	38	688,000	(*166*)	Western Amazon n=188
	Soybean expansion S.	20	2,870,000	(*52*)	

	America: 2000-2019				
	Soybean expansion Amazon *: 2000-2019	20	420,000	(*52*)	
	Anthropogenic forest loss: 2000-2017	18	540,000	(*26*)	
	Amazon fires*: 2003-2015	13	800,000	(*167*)	
	Amazon fires*: 2019	1	156,000	(*168*)	
	Amazon deforestation peak*: 2004	1	27,772	(*72*)	
Natural Global	LIP: Siberian Traps	252,000,000	7,000,000	(*169*)	LIP = Large Igneous Provinces
	LIIP: Ontong Java Plateau	120,000,000	1,500,000	(*151*)	
	Megariver captures stream orders 8-10	100,000,000	5,642,282	(*34*)	
	LIP: Deccan Traps	66,000,000	500,000	(*170*)	
	Megariver captures stream orders 6-8	10,000,000	253,195	(*171*)	
	Megariver captures stream orders 4-6	1,000,000	11,362	(*171*)	
	1 km bolide impacts	50,000	5,000	(*152*)	1 km diameter crater
	10 m bolide	500	2,150	(*152*)	Tunguska event, area deforested
	2.5 m bolide	50	1,875	(*152*)	Area deforested
Natural South America	Origins modern rainforest floras & faunas Western Gondwana	125,000,000	51,447,500	(*4*)	Western Gondwana = South America, Africa, Arabia
	Megathermal forests across South America	125,000,000	17,840,000	(*4*)	
	Final separation South America and Africa	100,000,000	51,447,500	(*4*)	
	Diversification of modern rainforest floras & faunas	64,000,000	17,840,000	(*4*)	
	E-O global cooling, contraction of rainforests to tropical latitudes	34,000,000	14,000,000	(*4*)	
	Separation Amazon & Atlantic	34,000,000	7,000,000	(*4*)	

biotas = Seasonally Dry Diagonal				
Marine regression, expansion lowland basins	34,000,000	3,000,000	(*4*)	
GAAR-landia	33,000,000	4,000,000	(*4*)	
Mega-river captures in Sub-Andean foreland	32,000,000	1,000,000	(*4*)	
Pebas mega-wetland system	22,000,000	1,000,000	(*4*)	
Expansion of C4 grasses & mammalian grazers	17,000,000	2,690,000	(*4*)	South American savannahs
Separation cis- & trans-Andean lowland biotas	12,000,000	2,000,000	(*4*)	Trans-Andean lowlands
Desertification at continental periphery	10,000,000	1,708,000	(*4*)	Patagonia, Atacama, Sechura, Goajira, Caatinga
Great Amazonian Biotic Interchange (GAzBI)*	10,000,000	1,600,000	(*152*)	
Rise of Fitzcarrald arch*	4,000,000	400,000	(*172*)	
Ice ages cycles: forast-savanah*	100,000	500,000	(*173*)	
Irion cycles: várzeas*	100,000	460,000	(*174*)	
Irion cycles: igapos*	100,000	320,000	(*174*)	
Megafauna extinctions - changes woody-savanna cover	10,000	290,000	(*174*)	
Ice ages cycles: shorelines	10,000	200,000	(*164*)	